A Method for Estimating Clear-Sky Instantaneous Land-Surface Longwave Radiation With GOES Sounder and GOES-R ABI Data

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***Abstract*—This letter presents new models for estimating clear-sky instantaneous longwave radiation over land surfaces using the Geostationary Operational Environmental Satellites (GOES) Sounders and GOES-R Advanced Baseline Imager (ABI) thermal infrared top-of-atmosphere (TOA) radiances. The method used in this study shares the same hybrid method framework designed for Moderate Resolution Imaging Spectroradiometer. We propose separate surface downward longwave radiation (LWDN) and upwelling longwave radiation (LWUP) models because the two components are dominated by different surface/atmospheric properties. A nonlinear model was developed to estimate LWDN, and a linear model was developed to estimate LWUP. The GOES-12 Sounder-derived LWDN, LWUP, and surface net longwave radiation (LWNT = LWUP-LWDN) were evaluated using one full-year of ground data from the Surface Radiation Budget Network. The root-mean-squared errors (rmses) are less than 22.03 W/m^2 at all four sites. Our study indicates that the hybrid method can also be applied to estimate LWUP using the future GOES-R ABI TOA radiances. The lack of a channel beyond 13.3 μm in the proposed ABI design may cause larger rmses when estimating LWDN.**

***Index Terms*—Geostationary Operational Environmental Satellite (GOES)-R Advanced Baseline Imager (ABI), GOES Sounder, land, longwave radiation, remote sensing, Surface Radiation Budget (SRB).**

I. INTRODUCTION

THE EARTH's Surface Radiation Budget (SRB) plays an important role in determining the thermal conditions of the atmosphere, oceans, and land. It is valuable for addressing a variety of scientific and application issues related to climate trends, land-surface modeling, and agriculture [3]–[5]. The surface longwave radiation budget [(SLRB), 4–100 μm] consists of surface downward longwave radiation (LWDN), upwelling longwave radiation (LWUP), and net longwave radiation (LWNT = LWUP-LWDN). LWNT is one of the two components—the other being surface net shortwave radiation—in surface net radiation, which is the key driving force for evapotranspiration. High-resolution SLRB (down to 1 km) are important diagnostic parameters for mesoscale land surface and atmospheric models, particularly over mountainous areas and other heterogeneous surfaces [6], [7]. However, previous studies [3]–[5], [8]–[12] have focused on estimating SLRB from coarse spatial resolution satellite data and cannot capture the detailed variations over heterogeneous surfaces. Wang and Liang [1] and Wang *et al.* [2] proposed a new framework to estimate high spatial resolution clear-sky SLRB using top-of-atmosphere (TOA) radiances from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the National Aeronautics and Space Administration Terra and Aqua Earth-observation system polar-orbiting satellites. However, MODIS Terra and Aqua only observe the Earth four times daily at a low altitude and may not meet temporal requirements of different applications [13].

National Oceanic and Atmospheric Administration (NOAA) Geostationary Operational Environmental Satellite (GOES) Sounders and MODIS are complementary when estimating SLRB over land. MODIS features global coverage and low temporal resolution (four overpasses per day) [14], and the GOES Sounders have a high temporal resolution (30 to 60 min) between the 20° N and 50° N latitudes [15]. The spatial resolution of GOES Sounders is coarser ($\sim$10 km) than MODIS but finer than the satellite data (20–40 km) used for generating the existing SLRB products [16]–[18]. The spatial and temporal resolutions of the future GOES-R Advanced Baseline Imager (ABI) thermal infrared (TIR) channels will be further improved to 2 km at every 5 min over the Continental U.S. (CONUS) region [15]. MODIS, GOES Sounders, and GOES-R ABI have similar TIR channels (see Table I). This letter presents new models for estimating instantaneous clear-sky LWDN and LWUP from GOES Sounders and GOES-R ABI TOA radiances. The models were developed using the same hybrid method framework originally designed for MODIS [1], [2]. Section II presents this general framework. The GOES Sounder models and validation results are discussed in Section III. Section IV examines the feasibility of applying the framework to GOES-R ABI observations. Lastly, Section V summarizes.

II. GENERAL FRAMEWORK OF THE HYBRID METHOD

The general framework of the hybrid method (see Fig. 1) consists of two steps. The first step is to generate simulated databases using extensive radiative transfer simulation. The physics that govern the SLRB are embedded in the radiative transfer simulation processes. The second step is to conduct a statistical analysis of the simulated databases to derive LWDN and LWUP models. Previous studies [19]–[21] have applied similar ideas to determine land-surface broadband albedo and surface insolation.

A radiative transfer simulation requires representative atmospheric profiles and emissivity spectra of different land surfaces. Theoretically, the greater the number of representative atmospheric profiles and emissivity spectra employed, the

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TABLE I
COMPARING GOES-12 SOUNDER, GOES-R ABI, AND MODIS TIR CHANNELS (ONLY CHANNELS RELEVANT TO SLRB ESTIMATION WERE LISTED; OTHER GOES SOUNDERS HAVE SIMILAR CHANNELS AS GOES-12 SOUNDER)

GOES 12 Sounder		GOES-R ABI		MODIS		Primary Use
Band	Central Wavelength (μm)	Band	Central Wavelength (μm)	Band	Central Wavelength (μm)	
1	14.71					Temperature sounding
2	14.37			**36**	14.235	
3	14.06			**35**	13.935	
4	13.64			**34**	13.635	
5	13.37	**16**	13.30	**33**	13.335	
6	12.66					
7	12.02	**15**	12.30	**32**	12.020	Surface temperature
8	11.03	**14**	11.20	**31**	11.030	
		13	10.35			
9	9.71	**12**	9.61	**30**	9.730	Ozone
		11	8.50	**29**	8.550	Water vapor
10	7.43	**10**	7.34	**28**	7.325	
11	7.02	**9**	6.95			
12	6.51			**27**	6.715	

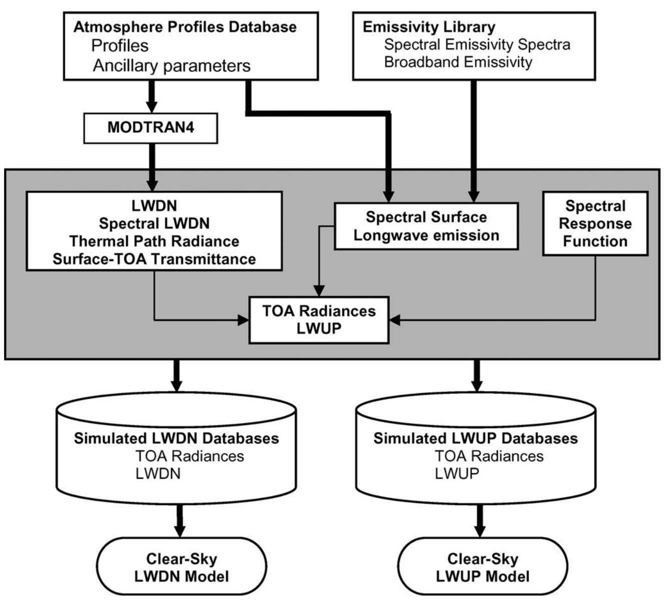

Fig. 1. Flowchart of the hybrid method framework.

better the model is derived. However, we had to limit the size of the simulated databases because radiative transfer simulation is time consuming and data-handling capacity of statistical software packages is restricted. Clear-sky LWDN is dominated by near-surface atmospheric temperature and moisture conditions but is not sensitive to surface emissivity (ε). Accordingly, we generated the LWDN simulated databases using a larger atmospheric profile database and a smaller emissivity library. LWUP is dominated by surface temperature (T_s) and ε but is not sensitive to atmospheric conditions. Therefore, a smaller atmospheric profile database and larger emissivity library were used for the LWUP simulated databases.

Atmospheric profile databases were generated using two years (2001 and 2004) of MODIS Terra-retrieved atmospheric product (MOD07_L2, v5) [22] over the North American continent. For each profile, the temperature and moisture values in layers below 10 km were resampled to fixed altitude levels. Representative profiles were selected by comparing new profiles with those already in the database and excluding similar profiles based on empirically determined similarity thresholds. Similarity is defined as the sum of the weighted ($w = 1/(A+1)$, where A is the altitude in km) absolute difference in temperature and moisture between two profiles at different altitude levels. The final profile database consists of $\sim$8000 profiles (for LWDN). A smaller database ($\sim$2000 profiles, for LWUP) was generated by further reducing the number of profiles using larger similarity thresholds. T_s, surface pressure (P), column water vapor (W), and surface elevation (H) that correspond to each profile are also available in the MOD07_L2 product. Surface air temperature (T_a), was linearly interpolated from MOD07_L2 temperature and pressure profiles and P.

The emissivity libraries for the LWDN and LWUP radiative transfer simulations are also different. The plant functional type (PFT) of each profile was identified using a collocated MODIS land cover product (totally, nine PFTs) [23]. For LWDN, one emissivity spectrum from the John Hopkins University emissivity library (nine spectra used, corresponding to nine PFTs) [24] was assigned to each profile based on its PFT. For LWUP, multiple emissivity spectra from the University of California Santa Barbara emissivity library (59 spectral used, similar spectra excluded) [25] were assigned to each profile based on its PFT to achieve a better representation of ε variations over land.

Separate simulated databases for LWDN or LWUP were produced using the aforementioned atmospheric profile databases and emissivity libraries. This study assumes a Lambertian surface. For each profile, LWDN (4–100 μm), spectral LWDN, thermal path radiance, and atmospheric transmittance were simulated using the Moderate Resolution Transmittance Code Version 4 [26]; 11 surface longwave-emission situations were calculated (T_s was assigned by offsetting T_a from -10 to 10 K, with an increment of 2 K). LWUP (4–100 μm) was synthesized using surface longwave emission, reflected LWDN, and broadband ε. TOA radiances were calculated at five fixed sensor viewing zenith angles (VZA $= 0^\circ, 15^\circ, 30^\circ, 45^\circ,$ and 60°). To facilitate statistical analysis, the simulated databases consisted of LWDN (or LWUP), TOA radiances, and supporting variables (broadband ε, H, P, T_s, T_a, and W). In total, $\sim$440 000 (for LWDN) or $\sim$720 000 (for LWUP) simulated situations were generated.

LWDN and LWUP models were derived using the simulated databases. We tested different formulations of these models based on physics that govern LWDN and LWUP. Stepwise regression was employed to identify the channels and nonlinear terms that are ideal for estimating LWDN and LWUP. Separate regression coefficients for the five fixed VZAs were estimated

TABLE II
GOES-12 SOUNDER NONLINEAR LWDN MODEL-FITTING RESULTS

VZA	0°	15°	30°	45°	60°
a_0	-44.8722	-51.6357	-72.1654	-120.3777	-
a_1	96.3724	97.1171	99.3169	106.5137	126.804
a_2	2.6209	2.5206	2.1459	1.5720	0.9204
a_3	1.4669	1.4733	1.5315	1.6141	1.8386
a_4	-27.1931	-26.9319	-26.3887	-25.1835	-
a_5	35.4864	35.1178	34.3086	32.0538	25.9863
a_6	-92.2204	-93.7095	-97.6262	-108.2041	-
a_7	43.5084	46.8090	56.2904	79.3296	131.608
a_8	-27.0000	-26.7329	-25.9316	-24.5630	-
a_9	-1.9935	-1.9968	-2.0179	-2.0717	-2.1967
Std. Err. (e)	14.78	14.82	14.91	15.13	15.63
R^2	0.936	0.936	0.935	0.933	0.930

for each model. The LWDN, or LWUP, at an arbitrary VZA was calculated using linear interpolation. We used all simulated data for deriving models. The models' performance, including root-mean-squared errors (rmse) and biases, was evaluated using ground measurements.

III. GOES SOUNDER SLRB MODELS AND EVALUATION

A. LWDN Model

Clear-sky LWDN is dominated by near-surface atmospheric temperature and moisture conditions. Accordingly, GOES Sounder channels 4–6 (lower tropospheric and near-surface air temperature), 7–8 (T_s), and 10–12 (atmospheric water-vapor content) were considered in our statistical analysis. The surface pressure effect in LWDN [9] was considered using Wang and Liang's method (using H as a surrogate of surface pressure) [1]. Equation (1) shows the GOES Sounder nonlinear LWDN model (similar to the MODIS nonlinear LWDN model)

$$F_d = a_0 + L_7\left(a_1 + a_2 L_{12} + a_3 L_{10} + a_4 L_5 + a_5 L_4 + a_6\frac{L_7}{L_8} + a_7\frac{L_5}{L_7} + a_8\frac{L_{11}}{L_8} + a_9 H\right) \quad (1)$$

where F_d is the LWDN; L_i is TOA radiance at channel i ($\mathrm{W/m^2/\mu m/sr}$); and a_j $(j = 0, 9)$ is the regression coefficient. Table II summarizes the GOES-12 Sounder LWDN model-fitting results at five VZAs (other GOES Sounders have nearly equivalent fitting results). The nonlinear model explains more than 93% of variations in the simulated databases, with biases of zero and standard errors (e) of less than 16 W/m^2 ($\sim$6% under typical conditions). H explains $\sim$1.5% of variations. The three ratio terms represent column water vapor and explain $\sim$1% of variations. Model performances were further evaluated using ground measurements in Section III-C.

B. LWUP Model

LWUP is dominated by T_s and ε. A linear model was developed to estimate LWUP using GOES Sounder channels 10, 8, and 7 (atmospheric water-vapor content and T_s, comparable with MODIS channels 29, 31, and 32) [2]

$$F_u = b_0 + b_1 L_7 + b_2 L_8 + b_3 L_{10} \quad (2)$$

TABLE III
GOES-12 SOUNDER LINEAR LWUP MODEL-FITTING RESULTS

VZA	0°	15°	30°	45°	60°
b_0	124.9927	125.9401	128.9878	135.2046	148.1727
b_1	-130.4156	-132.0319	-137.2860	-148.0604	-170.4925
b_2	153.7796	155.1242	159.4967	168.4509	187.0587
b_3	4.6375	4.8304	5.4884	6.9761	10.5636
Std. Err. (e)	2.99	3.04	3.21	3.64	4.95
R^2	0.999	0.999	0.999	0.998	0.997

where F_u is the LWUP, and b_j $(j = 0, 3)$ is the regression coefficient. Table III summarizes the GOES-12 Sounder LWUP model-fitting results. The model accounts for more than 99% of variations in the simulated databases, with biases of zero, and e less than 5.00 W/m^2.

C. GOES-12 Sounder Models Evaluation and Discussions

The GOES-12 Sounder LWDN and LWUP models were validated using one year's (2007) ground measurements from the SRB Network (SURFRAD) at four sites (Bondville, IL; Sioux Falls, SD; Penn State, PA; and Boulder, CO), with VZAs of less than the largest VZA considered in radiative transfer simulation (60°). The ground instruments (precision infrared radiometer, Eppley Laboratories) are elevated $\sim$8 m above the surface, with maximum signals from 45°, and an overall accuracy of 9 W/m^2 [27]. The footprint for LWUP is larger than 200 m^2. Clear-sky observations were identified using GOES-12 Sounder cloud product [28]. Manual screenings were used to remove obviously cloud-contaminated data points caused by failures within the cloud product.

Table IV presents the GOES-12 Sounder validation results. MODIS Terra validation results obtained from two former studies [1], [2] were also listed for comparison. Figs. 2 and 3 show validation plots at two representative sites: Bondville and Boulder. The bias patterns in GOES-12 Sounder-derived LWDN and LWUP are similar to those of MODIS. The LWDN biases range from -0.32 to 9.50 W/m^2 (average of 3.99 W/m^2). No significant relationship was found between biases and VZAs. However, LWDN tends to be underestimated at high T_s, T_a, and W conditions at all sites, due to the limited number of high temperature/moisture profiles of current profile databases. Consistent negative biases exist in GOES-12 Sounder-derived LWUP (from -0.86 to -14.27 W/m^2; average of -7.76 W/m^2). Similar negative biases were also observed in MODIS-derived LWUP (average of -8.75 W/m^2). A bias of -8 W/m^2 was adjusted to LWUP when LWNT was calculated, $(\mathrm{LWNT} = \mathrm{LWUP} + 8 - \mathrm{LWDN})$. The adjustment was estimated using the averaged biases in GOES-12 Sounder and MODIS-derived LWUP at all SURFRAD validation sites.

In all cases, the rmses of the GOES-12 Sounder-derived SLRB are less than 22.03 W/m^2, which is slightly larger than MODIS (see Table IV). However, the rmse is comparable with those of the existing data sets (21–33.6 W/m^2) [16]–[18]. The error caused by spatial mismatch between satellite observations and ground-instrument footprint is larger for GOES Sounder. Using 18 coincident clear-sky cases in 2007, the variability of the 1-km MODIS-derived SLRB within the GOES-12 Sounder footprint was studied at the Bondville site. The standard deviations of MODIS-derived LWDNs are $\sim$4 W/m^2, which are slightly smaller than those for LWUP (< 6 W/m^2, except

TABLE IV
COMPARING GOES-12 SOUNDER AND MODIS TERRA LWDN (NONLINEAR) AND LWUP (LINEAR) MODEL VALIDATION RESULTS

Unit: W/m^2	GOES-12 Sounder							MODIS					
	# Obs.	LWND		LWUP		LWNT		LWDN		LWUP		LWNT	
		Bias	RMSE	Bias	RMSE	Bias	RMSE	Bias	RMSE	Bias	RMSE	Bias	RMSE
Bondville	1740	-0.32	22.03	-3.68	16.69	4.63	20.52	-2.20	19.41	-9.49	17.75	3.97	19.12
Sioux Falls	1004	1.44	18.44	-14.27	19.59	-7.70	19.12	-2.65	16.87	-13.55	17.87	-2.43	17.08
Penn State	837	9.50	20.87	-0.86	14.61	-2.35	20.37	-0.52	16.73	-7.32	12.72	1.37	18.92
Boulder	747	5.33	18.12	-12.23	20.90	-9.55	19.24	9.72	20.35	-4.62	19.24	-9.69	19.38
Averaged	-	3.99	19.87	-7.76	17.95	-3.74	19.81	1.09	18.34	-8.75	16.90	-1.70	18.63

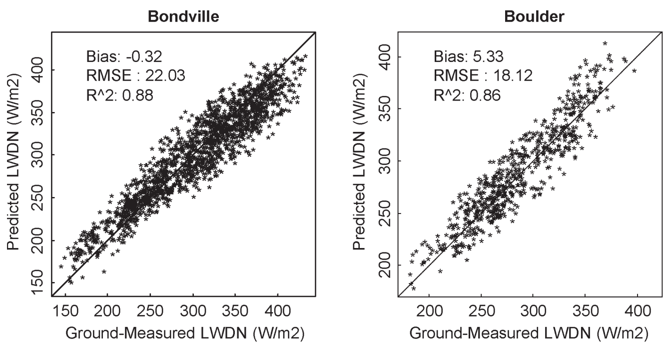

Fig. 2. GOES-12 Sounder-derived LWDN validation results at the Bondville and Boulder sites.

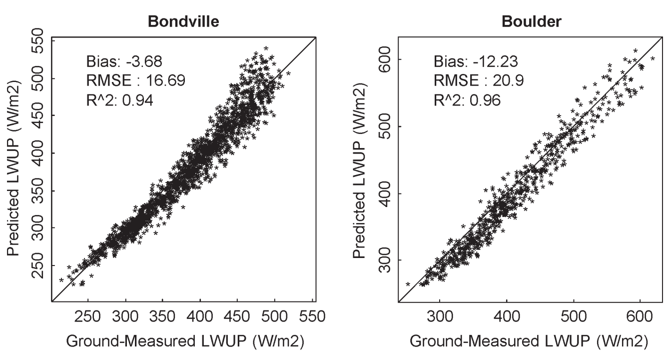

Fig. 3. GOES-12 Sounder-derived LWUP validation results at the Bondville and Boulder sites.

for one daytime case). The difference between the averaged MODIS-derived and GOES-derived SLRB is ~6 W/m^2.

It is more challenging to account for atmospheric water-vapor effects and ε angular effects at larger VZAs. Model-fitting results (see Tables II and III) indicated that LWDN and LWUP models have slightly larger e and smaller explained variance (R^2) at larger VZAs. Our validation results only give the model performances at VZAs between 45° and 60° because the VZAs of all four sites fall in this range. The MODIS LWDN and LWUP models were evaluated using data points that are nearly evenly distributed at all VZAs [1], [2]. The MODIS results indicated that the rmses for observations with VZAs $<= 30°$ are ~3 W/m^2 smaller than those with VZAs $> 30°$. Therefore, the overall GOES-12 Sounder rmses under all VZAs should be comparable with the rmses presented here.

The Lambertian surface assumption in the radiation transfer simulations may cause a larger error in LWUP over sparsely vegetated surfaces because of the directional effect in ε. However, no validation site is available to evaluate the performance of the GOES-12 Sounder model over such surfaces. Wang *et al.* [2] validated the MODIS LWUP model at a sparsely vegetated site (Desert Rock, NV) using two-year' ground data and at all VZAs. The linear MODIS LWUP model rmse over this site is ~25 W/m^2, which is smaller than that of an alternative temperature-emissivity method.

The atmospheric profile databases used in this study could be another source of errors. The databases were generated using atmospheric profiles retrieved from MODIS Terra (local overpass 10:30 A.M. and 10:30 P.M.). Wang and Liang [1] and Wang *et al.* [2] indicated that the databases represent MODIS Aqua overpass well. However, the databases may not represent all atmospheric conditions for GOES Sounder observations (every 60 min), particularly when T_a and T_s are similar.

IV. ESTIMATING SLRB FROM GOES-R ABI DATA

The first GOES-R series satellites, which are the next generation of NOAA geostationary satellites, are scheduled to be launched in 2015. SLRB is among the planned operational products of the GOES-R program [15]. Benefiting from the improved instrument technology and spatial/temporal resolutions, more timely and accurate SLRB may be retrieved using the anticipated GOES-R ABI data.

We investigated the feasibility of applying the hybrid method framework to the GOES-R ABI data, using the simulated spectral response functions from the Space Science and Engineering Center at the University of Wisconsin (Mr. T. Schmit, personal communication, 2007). The radiative transfer simulation and statistical analysis for ABI are similar to those for MODIS and GOES-12 Sounder. Equations (3) and (4) are the preliminary ABI (full system) LWDN and LWUP models, i.e.,

$$F_{d,\mathrm{GOES-R}} = c_0 + L_{15} \times \left(c_1 + c_2 L_{14} + c_3 L_{10} + c_4 L_9 + c_5 \frac{L_{15}}{L_{14}} + c_6 \frac{L_{16}}{L_{15}} + c_7 \frac{L_{11}}{L_{14}} + c_8 H \right) \quad (3)$$

$$F_{u,\mathrm{GOES-R}} = d_0 + d_1 L_{11} + d_2 L_{13} + d_3 L_{14} + d_4 L_{15}. \quad (4)$$

The ABI model-fitting results (see Fig. 4) are also similar to those of GOES Sounder and MODIS. No concerns exist for the LWUP model because all channels used in MODIS and GOES Sounder LWUP models are available in ABI. Moreover, ABI has an additional window channel at 10.35 μm that can also be used for estimating LWUP.

Following the general framework, LWDN may not be estimated accurately using the ABI data. ABI has only one temperature sounding channel at 13.3 μm (weighting function peaks at surface) and beyond. The atmospheric radiation above 500 m from the surface contributes ~20% of the total LWDN [3]. Wang and Liang's MODIS study [1] and the GOES Sounders' results indicate that a lower tropospheric temperature sounding

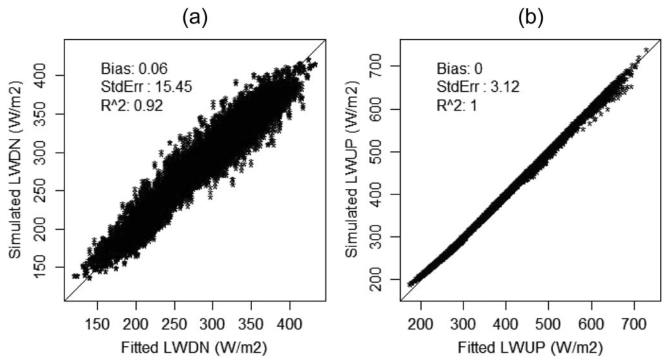

Fig. 4. GOES-R ABI (a) nonlinear LWDN and (b) linear LWUP model-fitting results.

channel at $\sim$13.64 μm (weighting function peaks at $\sim$2 km above surface) is necessary to provide atmospheric temperature information from above 500 m. We modified the GOES-12 Sounder LWDN model to use channels only available in GOES-R ABI. The modified model explains $\sim$1% less variations in the simulated database—primarily due to the lack of 13.64 μm channel. Ground validation results show that this modified model has large rmses (> 40 W/m^2) and biases (> 20 W/m^2 under high T_a conditions) at all sites. The GOES-R ABI was expected to have a companion advanced sounder (the Hyperspectral Environmental Suite) that featured longer wavelength coverage. Unfortunately, it was removed due to a budget shortfall.

V. Summary

This letter has presented new models for estimating instantaneous clear-sky LWDN and LWUP over land using GOES Sounders and GOES-R ABI TOA radiances. The models were derived from a hybrid method that shares the same general framework as that published by Wang and Liang [1] and Wang *et al.* [2]. The GOES-12 Sounder-derived LWDN, LWUP, and LWNT were validated using one-year SURFRAD ground measurements, with rmses of less than 22.03 W/m^2 at all sites. Our study indicates that the hybrid method can also be used to estimate LWUP using the future GOES-R ABI TOA radiances. However, the lack of channel beyond 13.3 μm in the proposed ABI design may cause larger rmses when estimating LWDN.

References

[1] W. Wang and S. Liang, "Estimation of high-spatial resolution clear-sky longwave downward and net radiation over land surfaces from MODIS data," *Remote Sens. Environ.*, vol. 113, no. 4, pp. 745–754, Apr. 2009.

[2] W. Wang, S. Liang, and J. A. Augustine, "Estimating high spatial resolution clear-sky land surface upwelling longwave radiation from MODIS data," *IEEE Trans. Geosci. Remote Sens.*, vol. 47, no. 5, pp. 1559–1570, May 2009.

[3] J. Schmetz, "Towards a surface radiation climatology: Retrieval of downward irradiances from satellites," *Atmos. Res.*, vol. 23, no. 3/4, pp. 287–321, Oct. 1989.

[4] R. G. Ellingson, "Surface longwave fluxes from satellite observations: A critical review," *Remote Sens. Environ.*, vol. 51, no. 1, pp. 89–97, Jan. 1995.

[5] G. Diak, J. Mecikalski, M. Anderson, J. Norman, and W. Kustas, "Estimating land surface energy budgets from space: Review and current efforts at the University of Wisconsin—Madison and USDA–ARS," *Bull. Amer. Meterol. Soc.*, vol. 85, no. 1, pp. 65–78, Jan. 2004.

[6] O. B. Christensen and J. H. Christensen, "Very high-resolution regional climate simulations over Scandinavia—Present climate," *J. Clim.*, vol. 11, no. 12, pp. 3204–3229, Dec. 1998.

[7] V. Masson, J.-L. Champeaux, F. Chauvin, C. Meriguet, and R. Lacaze, "A global database of land surface parameters at 1-km resolution in meteorological and climate models," *J. Clim.*, vol. 16, no. 9, pp. 1261–1282, May 2003.

[8] A. K. Inamdar and V. Ramanathan, "On monitoring the atmospheric greenhouse effect from space," *Tellus B, Chem. Phys. Meteorol.*, vol. 49, no. 2, pp. 216–230, Feb. 1997.

[9] H.-T. Lee and R. G. Ellingson, "Development of a nonlinear statistical method for estimating the downward longwave radiation at the surface from satellite observations," *J. Atmos. Ocean. Technol.*, vol. 19, no. 10, pp. 1500–1515, Oct. 2002.

[10] Y. Zhou, D. P. Kratz, A. C. Wilber, S. K. Gupta, and R. D. Cess, "An improved algorithm for retrieving surface downwelling longwave radiation from satellite measurements," *J. Geophys. Res.*, vol. 112, no. D15, p. D15 102, Aug. 2007.

[11] W. L. Smith and H. M. Wolfe, "Geostationary satellite sounder (VAS) observations of longwave radiation flux," presented at the Satellite Systems Measure Radiation Budget Parameters Climate Change Signal, Igls, Austria, Aug./Sep. 1983.

[12] R. K. Gupta, S. Prasad, and T. S. Viswanadham, "Estimation of surface temperature over agriculture region," *Adv. Space Res.*, vol. 19, no. 3, pp. 503–506, Mar. 1997.

[13] CEOS and WMO, "CEOS/WMO online database: Satellite systems and requirements," The Committee on Earth Observation Satellites and the World Meteorological Organization, 2000. [Online]. Available: http://www.wmo.int/pages/prog/sat/Databases.html

[14] W. L. Barnes, T. S. Pagano, and V. Salomonson, "Prelaunch characteristics of the Moderate Resolution Imaging Spectroradiometer (MODIS) on EOS-AM1," *IEEE Trans. Geosci. Remote Sens.*, vol. 36, no. 4, pp. 1088–1100, Jul. 1998.

[15] T. J. Schmit, M. M. Gunshor, W. P. Menzel, J. J. Gurka, and J. Li, "Introducing the next-generation advanced baseline imager on GOES-R," *Bull. Amer. Meterol. Soc.*, vol. 86, no. 8, pp. 1079–1096, Aug. 2005.

[16] *Radiation Budget*, ASDC, Hampton, VA, 2006. [Online]. Available: http://eosweb.larc.nasa.gov/HPDOCS/projects/rad_budg.html

[17] J. Francis and J. Secora, "A 22-year dataset of surface longwave fluxes in the Arctic," presented at the 14th ARM Science Team Meeting, Albuquerque, NM, Mar. 2004.

[18] S. K. Gupta, C. H. Whitlock, N. A. Ritchey, and A. C. Wilber, Clouds and the Earth's Radiant Energy System (CERES) algorithm theoretical basis document: An algorithm for longwave surface radiation budget for total skies (subsystem 4.6.3), Jun. 1997.

[19] S. Liang, "A direct algorithm for estimating land surface broadband albedos from MODIS imagery," *IEEE Trans. Geosci. Remote Sens.*, vol. 41, no. 1, pp. 136–145, Jan. 2003.

[20] S. Liang, J. Stroeve, and J. Box, "Mapping daily snow shortwave broadband albedo from MODIS: The improved direct estimation algorithm and validation," *J. Geophys. Res.*, vol. 110, no. D10, p. D10 109, May 2005.

[21] G. R. Diak, W. L. Bland, and J. Mecikaski, "A note on first estimates of surface insolation from GOES-8 visible satellite data," *Agr. Forest Meteorol.*, vol. 82, no. 1–4, pp. 219–226, Dec. 1996.

[22] S. W. Seemann, J. Li, W. P. Menzel, and L. E. Gumley, "Operational retrieval of atmospheric temperature, moisture, and ozone from MODIS infrared radiances," *J. Appl. Meteorol.*, vol. 42, no. 8, pp. 1072–1091, Aug. 2003.

[23] A. Strahler, D. Muchoney, J. Borak, M. Friedl, S. Gopal, E. Lambin, and A. Moody, MODIS Land Cover Product Algorithm Theoretical Basis Document (ATBD), ver. 5.0, Boston Univ., Boston, MA, May 1999.

[24] J. W. Salisbury and D. M. D'Aria, "Emissivity of terrestrial materials in the 8–14 μm atmospheric window," *Remote Sens. Environ.*, vol. 42, no. 2, pp. 83–106, Nov. 1992.

[25] Z. Wan, MODIS Land-Surface Temperature Algorithm Theoretical Basis Document, ver. 3.3, Univ. California, Santa Barbara, CA, Apr. 1999.

[26] A. Berk, G. P. Anderson, P. K. Acharya, J. H. Chetwynd, L. S. Bernstein, E. P. Shettle, M. W. Matthew, and S. M. Adler-Golden, *MODTRAN4 User's Manual*. Hanscom AFB, MA: Air Force Res. Lab., Space Vehicles Directorate, Air Force Materiel Command, 1999.

[27] J. A. Augustine, J. J. DeLuisi, and C. N. Long, "SURFRAD—A national surface radiation budget network for atmospheric research," *Bull. Amer. Meterol. Soc.*, vol. 81, no. 10, pp. 2341–2357, Oct. 2000.

[28] P. Minnis, L. Nguyen, W. L. Smith, Jr., M. M. Khaiyer, R. Palikonda, D. A. Spangenberg, D. R. Doelling, D. Phan, G. D. Nowicki, P. W. Heck, and C. Wolff, "Real-time cloud, radiation, and aircraft icing parameters from GOES over the USA," presented at the 13th American Meteorological Society (AMS) Conf. Satellite Meteorology Oceanography, Norfolk, VA, Sep. 2004.